4.0 LFG DESIGN CONSIDERATIONS

4.1 GENERAL

This chapter discusses parameters the designer should consider for the design of LFG control systems.

The design process for LFG control typically consists of two phases. Phase 1 is an investigation to determine the technical and economical viability of the LFG recovery system. Phase 2 is the design of the full-scale system.

4.2 PHASE 1: INVESTIGATION

The investigation phase typically consists of the following steps:

- collect and review existing data,
- conduct interviews and site inspection,
- review data base information,
- conduct a screening process, and
- conduct a field tests.

4.2.1 Data Collection

Existing site data can be obtained from available records on the site, and from regulatory, and other government agencies. These include permit documents, regulatory correspondence, waste receipt volumes, waste type, gas data, leachate data and ground-water data, closure date, etc. Information on the site will permit the designer to established a data base for completing design calculations. It will also allow the designer to determine whether additional data gathering activities are necessary.

4.2.2 Interview and Site Inspection

Interviews should extend to all concerned parties familiar with landfill operations including landfill owner, operator and appropriate officials. This information will provide the designer with the current status of the site, any current environmental problems or ones that could develop in the future.

Inspection of the site and its surroundings will aid the designer in verifying the data collected and at the same time configuring the conceptual design of the LFG collection and recovery system.

4.2.3 Review of Data Base Information

A review of data base information on existing facilities of the same type will provide the designer with up-dated technologies, their effectiveness and costs.

4.2.4 Conduct Screening

The preliminary design screening process should consider:

- recovery technique,
- regulatory requirements for collection and treatment,
- comparative cost, and
- advantages and disadvantages of each technique.

4.2.5 Field Tests

To implement LFG collection/treatment options, certain data are required to properly design a system and to select the appropriate gas recovery and control system. The data required include chemical characteristics of the gas and the gas-generation rate. For existing landfills, data can be collected as described in the following paragraphs. For new landfills, assumptions must be made on the chemical and physical characteristics of the gas based on historical data from similar installations.

4.2.5.1 Characterization of Gaseous Emissions

LFG composition is one of the determinations that is of principal interest in any evaluation of potential gas treatment methods. Some methods to collect LFG samples are: barhole probe, permanent gas monitoring probes, and gas extraction wells.

EPA has developed three test methods for proposal of air emission control regulations. These include Method 2E - Determination of Landfill Gas Production Flow Rate, Method 3C - Determination of Carbon Dioxide, Methane, Nitrogen, and oxygen from Stationary Sources, and Method 25C - Determination of NMOC in landfill Gas. Detailed of these methods are described in the EPA document EPA-450/3-90-011a, Air Emissions from Municipal Solid Waste Landfills- Background Information for Proposed Standards and Guidelines. The following paragraphs briefly describe these methods.

4.2.5.2 Determination of Gas Generation Rate: EPA Method 2E

EPA Method 2E measures LFG production flow rate from MSW landfills and is used to calculate the flow rate of NMOC compounds from landfills. Extraction wells are installed in a cluster of three or five dispersed locations in the landfill and a blower extracts the LFG from the wells. LFG composition, landfill pressure and orifice pressure differentials are measured and the LFG production flow rate is calculated.

4.2.5.3 Determination of Non Methane Organic Compounds: EPA Method 3C

EPA Method 3C applied to the analysis of carbon dioxide ($C0_2$), methane (CH_4), nitrogen (N_2), and oxygen (0_2) in samples from MSW landfills and other sources when specified in an applicable Subpart of the regulation.

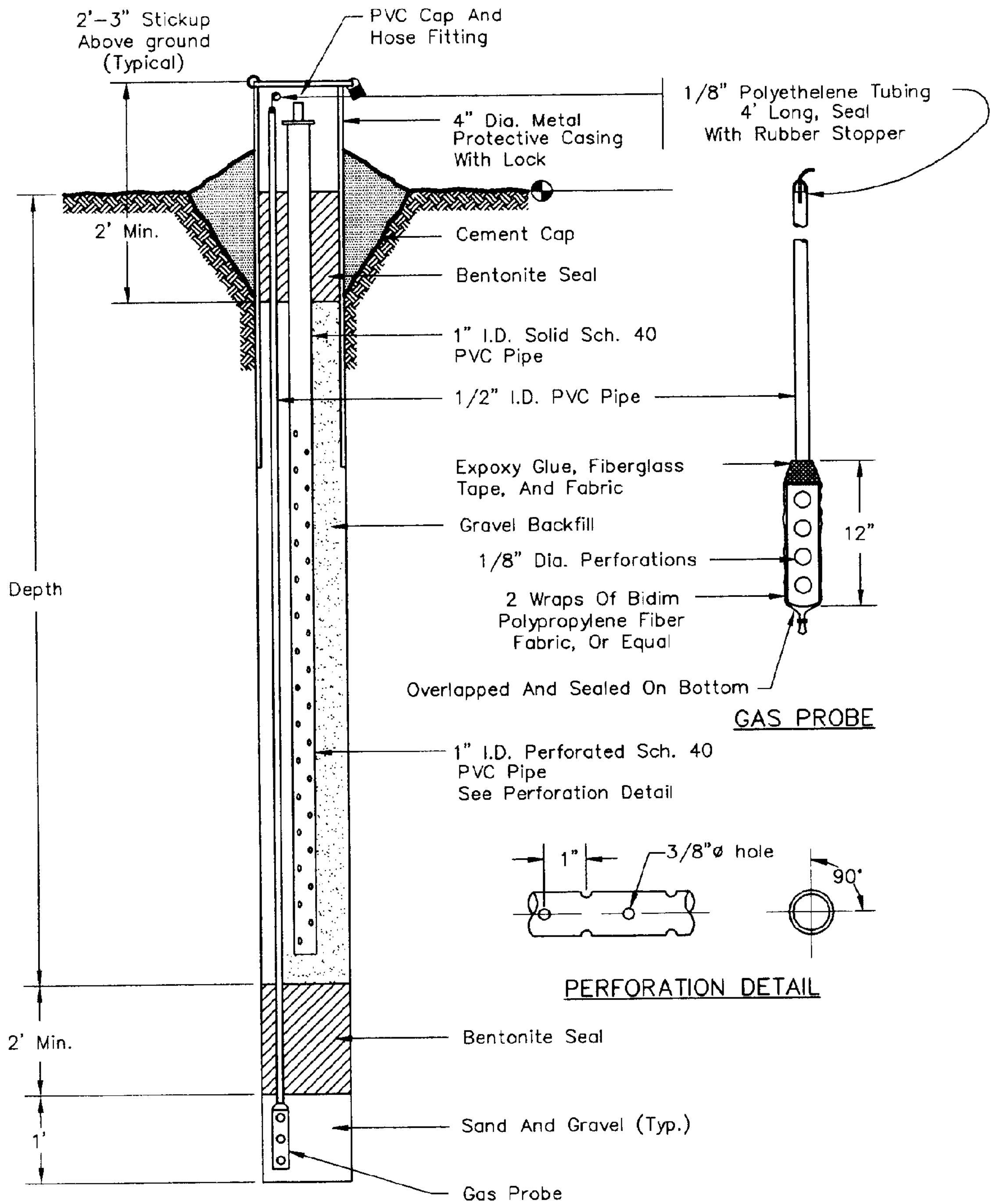
A portion of the sample is injected into a gas chromatograph (GC) and the $C0_2$, CH_4, N_2, and O_2 concentrations are determined by using a thermal conductivity detector (TCD) and integrator.

4.2.5.4 Determination of Non Methane Organic Carbon: EPA Method 25C

EPA Method 25C is applicable to the determination of NMOC (as carbon) in LFGs. A perforated sample probe is driven below the bottom of the landfill cover. A sample of the LFG is extracted with an evacuated cylinder. A portion of gas is injected into a gas chromatographic (GC) column to separate the NMOC from CO, $C0_2$ and CH_4. The NMOCs are oxidized to $C0_2$, and quantified with a flame ionization detector (FID). While this procedure is complex, it eliminates the variable response of the FID associated with different types of organic compounds. A typical gas probe monitoring detail is presented in Figure A-7.

4.2.5.5 Pilot-Scale Field Testing

Gas-phase permeability tests are the most common type of pilot-scale tests performed. These are generally used during the initial design stage of a gas recovery system. Gas-phase permeability tests provide the following design information:



TYPICAL GAS PROBE MONITORING DETAIL

FIGURE A-7

N.T.S.

(SOURCE 14)

- a measure of the pressure distribution associated with an applied vacuum,
- gas flow rates,
- contaminant concentrations and recovery rates,
- gas-phase permeabilities at the site, and
- moisture removal rates.

The gas-phase permeability tests (also called pneumatic pump tests) offer an alternative to indirect and laboratory methods for calculating air permeability. These tests tend to provide more realistic estimates of air permeability and are more appropriate for gas recovery testing. Air-phase permeability tests are described in several documents[2,5].

A number of investigators[18,19] have developed transient and steady-state solutions for air flow, which can be used for analysis of pneumatic pump test data.

4.3 PHASE 2: FULL-SCALE DESIGN

The full-scale design should start after selecting an LFG control system that is cost-effective and meets applicable regulations.

The primary design elements of the LFG management system include gas collection and treatment. Presented below are design considerations of these systems.

4.4 LFG COLLECTION

Two types of LFG collection systems are discussed:

- passive collection, and
- active collection.

4.4.1 Passive Collection Systems

Passive collection uses either collection wells or trenches to collect LFG. The efficiency of a passive collection system depends on good containment of the LFG. Collection wells and trenches typically use vent pipes which either discharge the gas to the atmosphere or to treatment.

4.4.1.1 Gas Wells

Passive collection systems rely on natural pressure or concentration gradients in the landfill to move the gas.

The construction of passive systems is similar to that of active wells which will be discussed in Section 4.4.2. However, the manifold connection shown would not be constructed. Additionally, elaborate well head assemblies are not required since monitoring and adjustment are not usually necessary. A good type of seal is always used to connect the geomembrane to the gas extraction well. The wells can be constructed as filling proceeds. However, if wells are placed in an existing landfill, they must be drilled into the waste.

Passive wells should generally be located about 10 to 15 meters (33 to 50 feet) from the edge of the wastes and typical not more than one well per acre. Additional wells may be needed further within the body of the wastes to intercept their full depth if the site is benched or sloping. A passive well vent is illustrated in Figure A-8.

4.4.1.2 Trench Collection Systems

Gas collection trenches can be used where vertical extraction wells are not practical, such as in areas where the refuse depth is shallow or where the liquid is high. A drawback of trenches is their tendency to draw in air if the seal over each trench is inadequate. Extreme care should be taken in the design of all vent systems to prevent them from being a source of infiltration through the cover.

Major advantages of trench systems include ease of construction and relatively uniform withdrawal influence areas. However, these trenches are susceptible to crushing as subsequent lifts of waste are placed and susceptible to severing and severe damage as a result of differential settlement of the waste pack. When placed below groundwater levels, these trenches are also subject to flooding. When designing trenches which will be installed below the expected high groundwater or

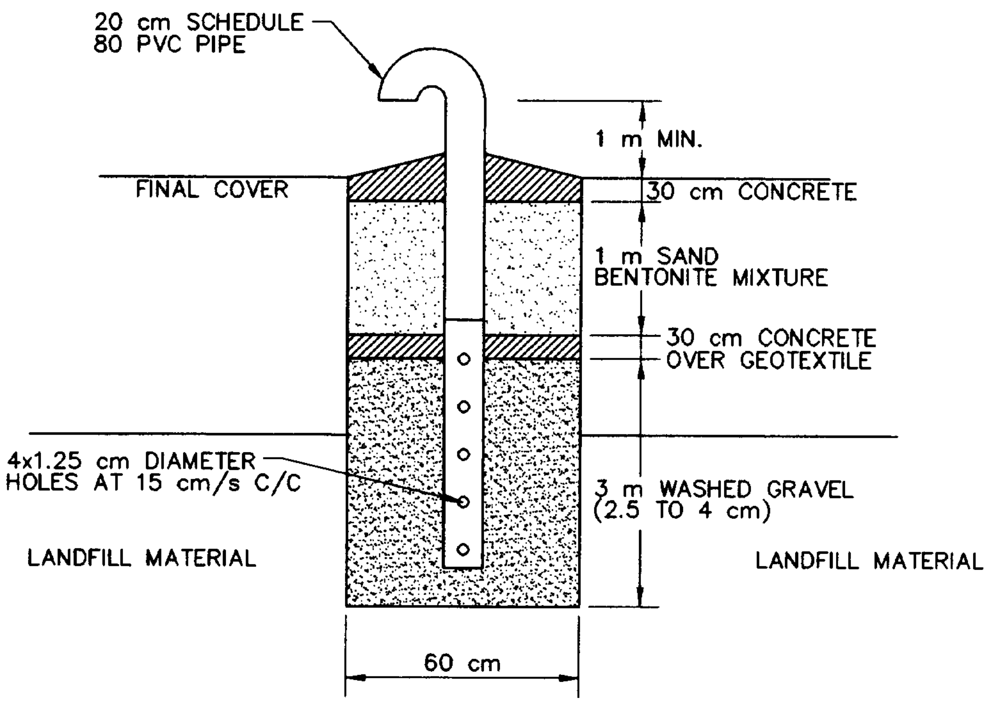


FIGURE A-8

PASSIVE GAS VENTS

(SOURCE 14)

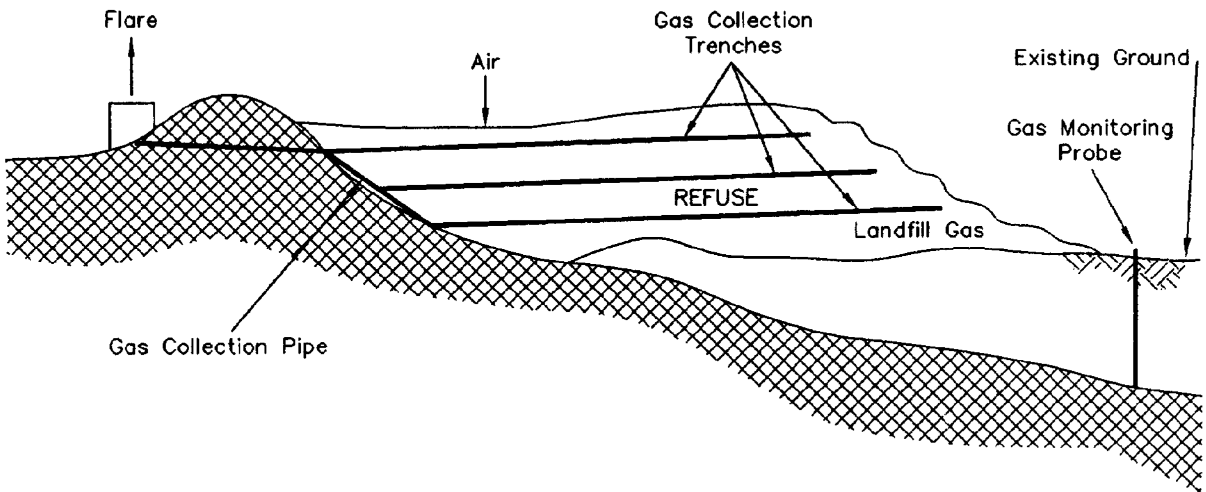
leachate levels, measures should be taken to avoid drawing water into the gas collection system.

The trenches can be vertical or horizontal at or near the base of the landfill. A vertical trench is constructed in much the same manner as a vertical well is constructed. For a new site, horizontal trenches are installed within a landfill cell as each layer of waste is applied. The distance between layers should be no greater than 5m (15 feet). This allows for gas collection as soon as possible after gas generation begins and avoids the need for above-ground piping which can interfere with landfill maintenance equipment. Additional "legs" of the system are connected to the manifold as the landfill grows in areal size or height. Figure A-9 illustrates a horizontal trench collection system.

The horizontal trench pipes may be constructed of perforated polyvinyl chlorides (PVC), high density polyethylene (HDPE), or other suitable strength nonporous material. Due to the corrosive nature of LFG and condensate, corrugated steel is usually not used. The trench should be about 1 meter (3 feet) wide, filled with gravel of uniform size and extend into the refuse about 1.5 m (5 feet) below the landfill cap layer. Trenches should be located between the waste fill and the gas barrier or side of the site.

The side of the trench nearest to the property boundary should be sealed with a low-permeability ($< 10^{-9} m \bullet s^{-1}$) barrier material, such as a synthetic geomembrane to prevent gas migration. The remainder of the trench should be lined with a filter fabric to prevent clogging of the permeable medium.

The gas collection piping enclosed in the trench gravel pack is connected to surface vent pipes of similar construction as the collection piping. Vent pipe spacing should be determined from monitoring and site investigation data, but should generally not be greater than 50 meters apart. Passive vents can be used in combination with horizontal trenches by connecting vents to the pipes with flexible (i.e., settleable) hosing. The flexible hose between the extraction well or trench and the collection header system allows differential movement.



HORIZONTAL TRENCH COLLECTION SYSTEM

FIGURE A-9
(SOURCE 2)

Because of its horizontal layout, the collection header system would be expected to settle more than a vertical extraction well. This flexible connection allows more movement than would be possible if the two pipes were rigidly connected. Sampling ports can be installed allowing monitoring of pressure, gas temperature and concentration, and liquid level.

4.4.2 Active LFG Collection Systems

As described previously, an active collection system consists of a mechanical blower or compressor attached to a system of gas extraction wells or collection trenches. A pressure gradient is created in the wells or trenches, thereby forcing the removal of gas from the landfill. The gas is then piped to a flare, cogeneration unit or other treatment system.

The effectiveness of an active LFG collection system depends greatly on the design and operation of the system. An effective collection system should be designed and configured so as to:

- handle the maximum LFG generation rate,
- effectively collect LFG from all areas of the landfill, and
- provide the capability to monitor and adjust the operation of individual extraction wells and trenches.

Air intrusion is a major concern in the design of the active LFG collection system. Air intrusion may naturally permeate through the landfill cover and into the refuse. Natural permeation is particularly severe in arid regions where dry cover soils are easily penetrated by air.

An active collection system has four major components:

- gas extraction wells (or horizontal trenches),
- gas moving equipment,
- LFG treatment units, and
- condensate removal and disposal units.

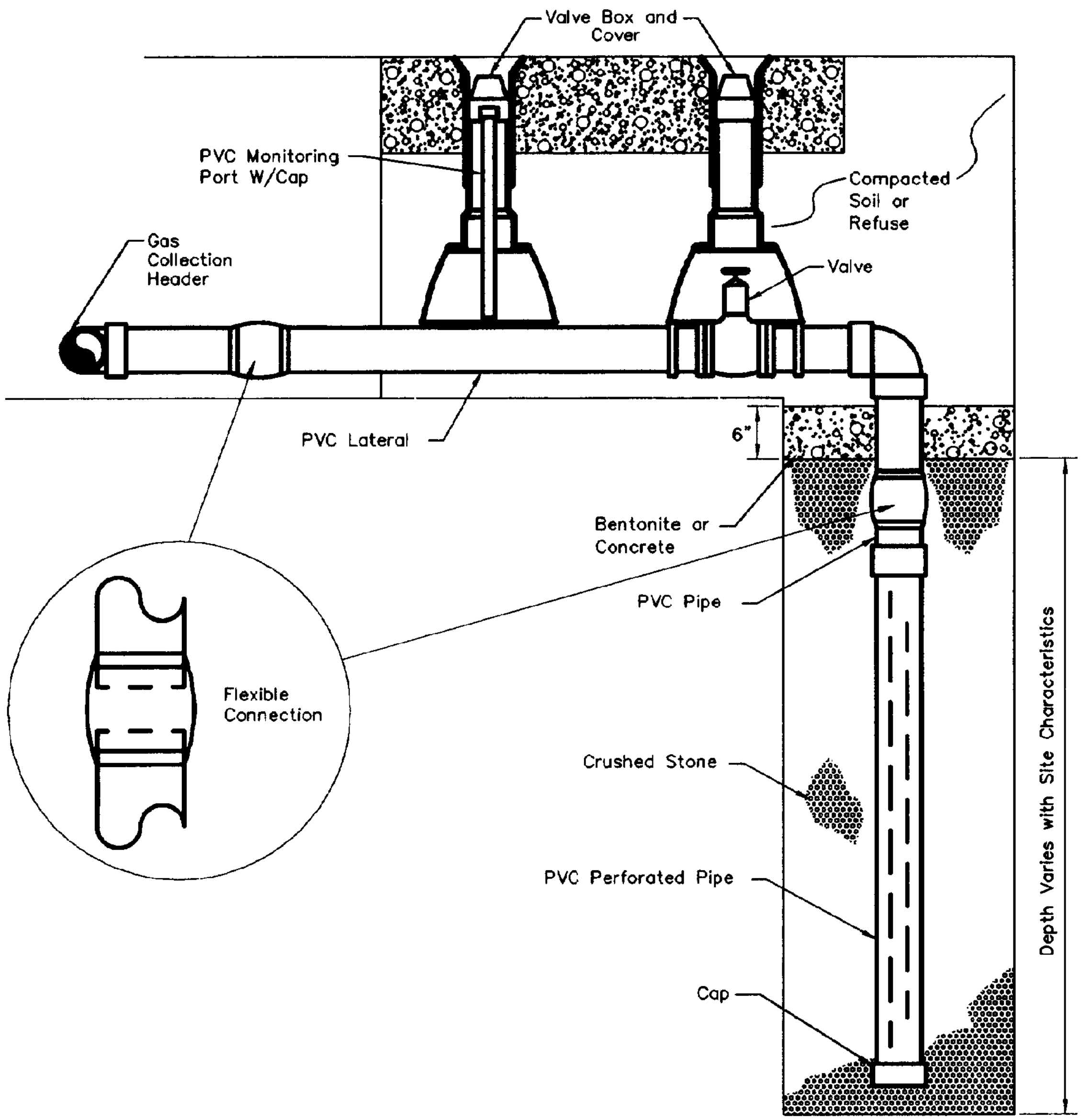
4.4.2.1 Gas Extraction Well Construction

LFG extraction wells are installed around the perimeter and into the center of the landfill. The extraction well is generally constructed of PVC, HDPE, fiberglass, stainless steel, or other suitable nonporous material. Pipe diameters vary but generally are no smaller than 5 cm (2 inches) in diameter and no larger than 30 cm (12 inches) in diameter. It is recommended that the bottom ¾ of the pipe be perforated with ½-inch-diameter holes spaced at 90 degrees every 6 inches. Slotted pipe having equivalent perforations is also suitable. Wells are typically constructed in 30 to 100 cm (12 to 36 inch) diameter boreholes. Upon insertion of the casing into the borehole, the remainder of the well excavation is backfilled with crushed stone. The crushed stone gives the extraction well a larger effective diameter from which gas can be drawn.

In unlined landfills, wells are constructed to either the base of the landfill or the water table. However, in lined landfills, wells are typically constructed to 75 percent of the landfills total depth in order to avoid damaging the liner. The screened interval of an LFG extraction well typically extends from the bottom of the well to a point at least 5 feet below the landfill surface. Slip couplings are also used for deep wells to account for differential settlement. Slip couplings should be designed to withstand circumferential pressure without collapsing. Each well head is typically designed with a butterfly or ball valve for regulating the applied pressure to the wellhead. A typical active vertical extraction well configuration is presented in Figure A-10.

4.4.2.2 Spacing and Radius of Influence

The spacing of LFG extraction wells is generally determined from the radius of influence of individual wells. This radius is described as the distance from the center of a well to a point away from the well where the steady-state-pressure gradient resulting from the blower is 0.1 inch of water. Accordingly, any CH_4 generated beyond the radius of influence would not be collected by the extraction wells.



ACTIVE VERTICAL WELL EXTRACTION WELL

FIGURE A-10
N.T.S.
(SOURCE 2)

In order to obtain a representative well spacing for the landfill, several pump tests should be performed so that waste compaction variability can be taken into consideration. Due to the costs associated with conducting these tests, there have been several theoretical models developed to estimate the vacuum-radius of influence relationship. Typical negative pressures at the well head range from about 127 to 380 mm (5 to 15 inches) of water column. Typical well spacings range from approximately 50 to 300 feet, depending on the radius of influence for each well.

The desired method for determining effective well spacing at a specific landfill is to use field measurement data. Pump tests with monitoring probes at incremental distances from the test well will indicate the influence of a given negative pressure at that location.

The EPA Methods specified in the New Source Performance Standards (NSPS) draft rule (March 1991) use Darcy*s Law to establish the vacuum/radius of influence relationship. Knowledge of both daily and final cover materials used in landfill construction, gas properties including density and viscosity, the permeability of the porous media (both the refuse and cover), and the LFG pressure are needed. Because such extensive data are rarely available or accurate, EPA has established a default maximum radius of influence of 60 m (200 feet) in revisions for publication of the final NSPS scheduled for December 1994. Use of this default parameter or the theoretical modeling is generally acceptable for estimating the radius of influence.

As noted above, use of the theoretical models based on Darcy*s Law requires estimation of several parameters. The parameters required include:

- intrinsic permeability of the refuse,
- current gas production rate of the landfill,
- static pressure at the wellhead,
- viscosity of the LFG,
- radius of the extraction well;

- length of well screen; and
- radius of influence of the well borehole.

Of these parameters, the intrinsic permeability of the refuse is the most difficult to predict. This parameter can vary several orders of magnitude between and within a landfill. This parameter has a large impact on the radius of influence predicted by the methodology. If the designer wishes to use the model for prediction of the radius of influence about a well, it is recommended that the model be used to solve the refuse intrinsic permeability to verify that the remaining parameters used predict a value for the intrinsic permeability which falls within a common range of intrinsic permeabilities for refuse ($1x10^{-7}$ to $1x110^{-12}$ cm^2).

The static pressure at the well head is the difference between landfill internal pressure and the atmospheric pressure and is the design vacuum pressure at the well head. The magnitude of the static pressure is a function of how much LFG is being produced and how impervious the capping materials are to gas migration. Where gas production rates are high and the landfill cover impervious, static pressures at the wellheads can be as high as 375 mm (15 inches) water column (wc). It is more common for wells to have static pressures in the range of 180 to 255 mm (7 to 10 inches) wc.

Viscosity of the LFG will be a function of the composition, the pressure and the temperature of the LFG. The viscosity can generally be approximated assuming the gas is composed of 50% CH_4 and 50% CO_2. At 0^0C and at atmospheric pressure, a 50% CH_4 and 50% CO_2 gas has a viscosity of $1.21x10^{-5}$ Pa.sec.

The intrinsic permeability can be computed as follows:

$$k_i = \frac{P_v * R^2 * \ln(R/r) * \mu_{lfg} * \rho_{ref} * Q * E_a}{M * (P_1^2 - P_v^2) * (WD/L)} \qquad (2\text{-}13)$$

where,

k_i = intrinsic permeability of refuse, cm^2 (ft^2)
P_1 = gage internal landfill pressure, Pa/m^2 (lbs/ft^2)
P_v = gage vacuum pressure at wellhead, Pa/m^2 (lbs/ft^2)
R = radius of influence, m (ft)

r = radius of well borehole, m (ft)
μ_{lfg} = viscosity of LFG, Pa.sec (lb-mm/ft^2
D_{ref} = refuse density, kg/m^3 (lb/ft^3)
Q = LFG generation rate, m^3/sec (ft^3/min)
E_a = efficiency of collection system, (1=100%)
M = Landfill capacity, Mg (lbs)
WD = Well screen length, m (ft)
L = Landfill depth, m (ft)

For the design purpose, a value of 1.0 is normally used for the efficiency, E_a, of collection system.

4.4.2.3 Number of Extraction Wells

The factors affecting the number of extraction wells selected are well radius of influence and spacing, and landfill geometry. Some overlap of influence zone is desirable for the perimeter wells of a system designed for control of gas migration to ensure that effective control is obtained at points between wells along the landfill boundary. Gas extraction rate and radius of influence are dependent on one another, and individual well flow rates can be adjusted after the recovery system is in operation to provide effective migration control and/or efficient CH_4 recovery.

4.4.3 Gas Moving Equipment

Gas moving equipment includes :

- pipeline header system, and
- compressors and blowers.

A pipeline header system conveys the flow of collected LFG from the well or trench system to the blower or compressor facility. A typical header pipe is made of PVC or HDPE and is generally 15 to 60 cm (6 to 24 inches) in diameter depending on the flow rate through each section of the pipe. The size and type of blower is a function of the total gas flow rate, total system pressure drop, and vacuum required to induce the pressure gradient.

4.4.3.1 Pipeline Header System

Collection header pipes are connected to the gas extraction wells by means of laterals constructed of flexible tubing to allow some movement between the two systems during settlement. In colder climates, the header pipe is often installed above the low permeability layer of the capping system. In warmer climates, the header system can be installed above the surface of the landfill. The exposed collection header may be subject to periodic freezing and may constitute an eyesore; however, it is very beneficial to have the pipe above ground for ease of maintenance.

Landfill settlement occurs from increased vertical stresses resulting from the refuse and cover materials and biological decomposition of the waste material. Differential settlement of the landfill can cause structural damage to the piping in the form of sags and breaks, consequently, a collector header that is not buried will be easier to repair. Other factors to be considered include the potential of vandalism and the intended end use of the site.

The basic elements in the design of the gas collection header system are the header pipe size, pipe material, pipe slope, and location of condensate traps. These will be discussed in the following sections.

Header Pipe Size. LFG headers are sized based on the design flows generated from the well system. Each section of the header should be designed to transmit the design volumetric flow rate at a velocity that will minimize friction losses and condensate losses in the header system. The first step in estimating the diameter of the header is to estimate the flow rate through each section of header. The designer can calculate these values by dividing the entire gas production potential as described in Section 4.2.2 by the total linear footage of perforated well screen for the system. This calculation will provide an estimate of gas flow rate per linear foot of pipe. The gas flow from each well can then be estimated by multiplying the length of well screen of each well by the flow rate per linear foot of screen.

The information should then be compiled on a spread sheet. The diameter of each header pipe can then be calculated using one of the following equations:

$$\text{Diameter}^{(17)} = 1.414 * (W^{0.408}/D^{0.343}) \qquad (2\text{-}14)$$

where,

W = flow rate, (1,000 lb/hr)
D = gas density (lb/ft^3)
1.414 = conversion factor

or

$$\text{Diameter}(2) = W/2000\ ft.sec^{-1}$$

where,

W = flow rate, (1,000 lb/hr)
2,000 = minimum velocity, ft/sec

In general, pipe diameters in the header system should be no less than 10 cm (4 inches) in diameter; a 15-cm (6 inches) diameter is typical. Pipe diameters as large as 325 cm (14 inches) can be installed, however, the feasibility of installing diameters of this magnitude will be a function of the allowable cover depth to prevent freezing. Pipe diameters greater than 325 cm (14 inches) are generally not used; in these cases, gas flow should be directed to a separate header line.

LFG collection systems must be designed in a manner such that condensate will not pool inside the headers. Minimum header slope must be maintained throughout the design life of the system, and landfill settlement must be accounted for in the layout of the header system. A minimum header slope of 2 percent is often used. Landfill settlement results from increased vertical stresses resulting from the refuse and cover materials and biological decomposition of the waste material. From these variables, primary and secondary settlement are calculated, and a final slope after settlement can be predicted.

The header system should be designed to allow LFG and condensate flowing in the same direction to maximize use of the heat of the gas to prevent condensate from freezing. Condensate sumps should be located at all low points in the header system to prevent clogging of the header.

4.4.3.2 Compressors and Blowers

Several types of compressors and blowers are used to remove LFG including multistage centrifugal blowers, regenerative blowers, rotary lobe compressors, and liquid ring vacuum compressors. Gas quality, peak gas flow rates, design vacuum pressure, and the pressure required for in-line processing of the gas are key parameters used to select a specific LFG compressor and blower.

Centrifugal Blowers. Centrifugal blowers are classified as constant pressure (vacuum) variable volume. The flow rates are only limited by the horse power (HP) of the motors and may be achieved across the entire performance curve from the surge point (low flow) and high flow capacity. Centrifugal blowers can be single stage, having only one impeller, or can be multistage having two or more impellers mounted in the same casing.

Single stage centrifugal blowers are typically used for applications requiring vacuums of less than 80 inches of water. These blowers are compact and produce an oil-free LFG flow. The principle of operation is as follows: Air enters the impeller in the axial direction and discharges radially at high velocity. The change in diameter through the impeller increases the velocity of the gas flow. The dynamic head is converted into static head, or pressure through a diffusion process that generally begins within the impeller and ends in a radial diffuser and scroll outboard of the impeller.

A multi-stage impeller creates pressure through the use of centrifugal force. A unit of LFG enters the impeller and fills the space between two of the rotating vanes. The LFG is thrusted outward toward the casing and then is sent to the vanes of another rotating impeller. This process continues regenerating the pressure many times until the air reaches the outlet.

<u>Advantages of Centrifugal Blowers</u>:

- can deliver variable volume at constant speed;
- use less power for lower flows;
- require low maintenance;
- allow for higher head pressures;
- operate on a single shaft with up to 11 impellers, typically at 3,500 rpms;
- produce a smooth, non-pulsating flow when operating at any point beyond the surge range;
- produce less noise; and
- can be equipped with auto shutdown;

<u>Disadvantages of Centrifugal Blowers</u>:

- surge protection is required;
- impellers will not tolerate the ingestion of large slugs of water/condensate;
- entrainment separators must be used; and
- impellers must be made of corrosion-resistant material due to the presence of H_2S in most LFG.

<u>Regenerative Blowers</u>. The Regenerative blower is one type of non-positive displacement and consists of a multi-stage blade impeller which rotates in a stationary housing. A unit of air enters the impeller and fills the space between two of the rotating vanes. As the blower impeller rotates, centrifugal force moves the air molecules from the root to the tip of the blade, around the housing contour, and then turned back by the annular shaped housing down to the base of the succeeding blade where it is hurled outward. This regenerative action provides

staging effect to increase pressure differential which depends on the speed of the rotating impeller. This process continues regenerating the pressure until the air reaches the outlet.

Multistage regenerative blowers are available in capacity up to several hundred cubic feet per minute and typically are used for a high range of vacuum levels (180-190 inches of water).

Advantages of Regenerative Blowers:

- Is a compact unit;
- Produce an oil-free air flow;
- can deliver variable volume at constant speed;
- allow for higher head pressures;
- operate on a single shaft with up to 11 impellers, typically at 3,500 rpms;
- produce a smooth, non-pulsating flow when operating at any point beyond the surge range;
- can be equipped with auto shutdown;

Disadvantages of Regenerative Blowers:

- surge protection is required;
- impellers will not tolerate the ingestion of large slugs of water/condensate;
- entrainment separators must be used; and
- impellers must be made of corrosion-resistant material due to the presence of H_2S in most LFG.

<u>Rotary Lobe Compressors</u>. Rotary lobe compressors are commonly referred to as positive displacement (PD) blowers. These compressors are classified as constant-volume and variable-pressure machines. Volume can only be varied by speed change in rotating lobes via a variable frequency controller (VFC) or sheave adjustment ratio change. Rotary lobe compressors are typically used for a medium range of vacuum levels (20 to 160 inches of water). Rotary lobe compressors consist of a pair of matched impellers rotating in a stationary housing with inlet and outlet ports. The impellers, oriented in opposite directions, trap a volume of gas at the inlet and move it around the perimeter to the outlet. Rotation of the impellers is synchronized by timing gears which are keyed into the shaft.

Oil seals are required to avoid contaminating the air stream with lubricating oil. These seals must be chemically compatible with the site contaminants. When a belt drive is employed, blower speed may be regulated by changing the diameter of one or both sheaves or by using a variable speed motor.

<u>Advantages of Rotary Compressors</u>:

- high discharge pressure at fixed flow rates.

<u>Disadvantages of Rotary Compressors</u>:

- Noisy,
- fixed flow rates (constant volume variable pressure;
- reducing flow rates will decrease the system pressure;
- higher compressor maintenance (oil and greasing on a regular basis), and
- Oil seals must be chemically compatible with gas contaminants.

Liquid Ring Vacuum Compressors. These vacuum pumps transfer both liquid and gas through the pump casing. Centrifugal force acting on the liquid within the pump causes the liquid to form a ring around the inside of the casing. Gas is trapped between rotating blades and is compressed by the liquid ring as the gas is forced radially inward toward a central discharge port. After each revolution the compressed gas and accompanying liquid are discharged. Vacuum levels close to absolute vacuum (i.e., absolute pressure equals zero) can be generated in this manner. These pumps generate a waste stream of liquid that must be disposed of properly. The waste stream can be reduced by recycling the liquid; however, a cooling system for the liquid stream may be needed to avoid overheating the pump. Figures A-l1, A-12, and A-13 illustrate the configuration of blowers and compressors utilized in LFG recovery systems.

Advantages of Liquid Ring Vacuum Compressors:

- can generate a vacuum level close to absolute vacuum (i.e., absolute pressure equals zero).

Disadvantages of Liquid Ring Vacuum Compressors:

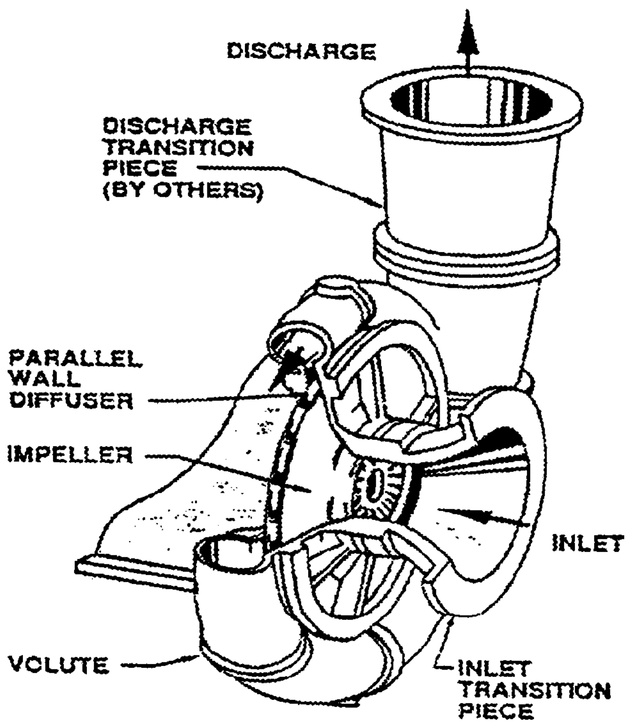
- produce a waste stream of liquid that must be disposed of properly.

The gas mover (blower, or compressor) systems should be designed to handle the peak LFG flow rate over the life of the LFG project.

Sizing of a blower/compressor is based on:

- Total flow, Q_{total} for the entire landfill;
- Design operating pressure; and
- The estimated headloss in the system.

The sizing of the blower is a function of the flow rate, static pressure required at each wellhead and estimated headloss in the system. Following completion of the header layout and calculation of the header diameter, an estimation of the total



<u>Figure A-11</u>
Centrifugal Blower
Courtesy of Roots Dresser

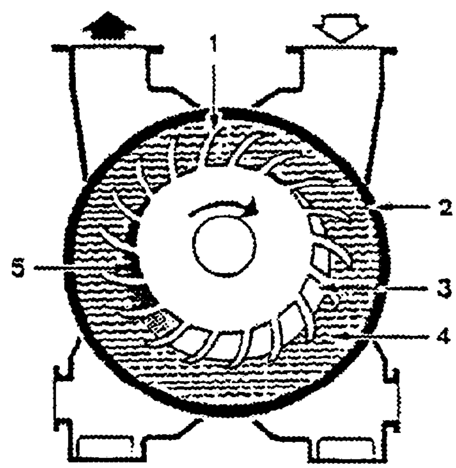
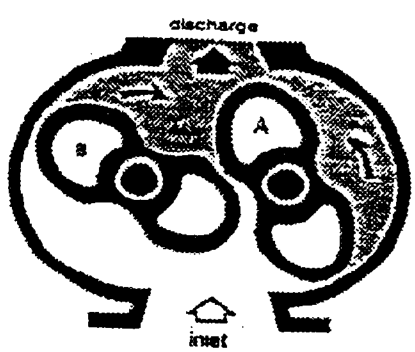


Fig. 6:31 Sectional view of a liquid-ring compressor
1. impeller
2. casing
3. intake port
4. working liquid
5. discharge port

<u>Figure A-12</u>
Liquid Ring Air Compressor
Courtesy of Atlas Copco



<u>Figure A-13</u>
Positive Displacement
Courtesy of Roots Dresser

pipe losses due to friction should be computed. Methods used in the analysis of water distribution systems are used in design of the LFG collection system. Pipe losses can be calculated through the use of Darcy-Weisbach equation and the Moody Diagram[14] for friction factor in the pipe versus Reynold's number and relative roughness.

Selection of blowers should be based on the following:

- cost effectiveness;
- simplicity of installation;
- long-life expectancy;
- minimum maintenance;
- variable load capacity;
- a low gas leakage rating under operating conditions; and
- safety of operation.

Some blowers tend to leak LFG around the shaft bearing. These blowers should be limited to outdoor use only.

4.4.4 Non-Energy Recovery Systems

4.4.4.1 Flare

A flare system is used to burn the LFG in a controlled environment to destroy harmful constituents and dispose of it safely to the atmosphere. The operating temperature is a function of gas composition and flow rate. LFG composition and flow rate are variable and somewhat unpredictable with a maximum of approximately 500 Btu per cubic foot when it contains approximately 50% CH_4. Consequently, when the Btu loading derived from LFG is outside the flare design range, auxiliary fuel is required at the flare.

The elements of combustion that must be addressed in the design of a LFG flare are: residence time, operating temperature, turbulence, O_2 and flame arrestor. These elements are interrelated and, to some extent, dependent on each other. Residence time, operating temperature, and burner design must all be considered in selecting and evaluating LFG combustion equipment.

Adequate time must be available for complete combustion. The temperature must be high enough to ignite the gas and allow combustion of the mixture of fuel and 0_2. The residence time in a combustor must be sufficient for hydrocarbons to react with the O_2. Residence times for VOCs can vary from 0.25 to 2.0 seconds, and solid particles, such as carbon, may require as long as 5 seconds for complete destruction.

The operating temperature of the combustor depends upon the material to be combusted. The temperature should be about 148 to 260^{0}C (300 to 500^{0}F) above the auto-ignition temperature of the waste gas. CH_4 autoignites at 540-760^{0}C (1004-1,004^{0}F), thus a minimum operating temperature of 760^{0}C (l,400^{0}F) is often specified. A temperature that is too high may cause refractory damage as well as production of excess NO_x, while a temperature that is too low may result in the production of excess carbon monoxide and unburned hydrocarbons.

There must be enough turbulence to mix the fuel and O_2 and enough O_2 to support combustion. Mixing the LFG and air at the burner tip is critical to proper operation of the flare. Proper mixing and adequate turbulence will create a uniform mix of LFG and air in the combustion zone, whereas improper mixing will result in flue gas stratification, which contributes to high emissions and unstable operation.

Operating at high flow rates and tip velocities requires flame stabilizers to prevent the flame from extinguishing itself. Windshields allow the flame to establish itself and resist high wind conditions. Automatic pilots sense the LFG flame and automatically relight the flare when necessary, thereby saving energy costs.

The basic flare unit consists of the following components:

- a multi-orifice burner,
- a burner chamber,
- an automatic combustion air control system (dampers),
- an electric pilot ignition system,
- sampling ports,
- flare control panel,

- temperature controller (interlock the flare stack),
- a flame arrestor, and
- emission control.

The multi-orifice burner and burner chamber are enclosed in a stack containing refractory insulation. Typical stack height of the flare is 6 to 10m (20 to 30 feet). An automatic air control system consist of dampers which operate based on the temperature controller. The dampers provide ambient air to the flare interior for combustion and for controlling the exit gas temperature. The temperature controller should have a high temperature interlock to prevent damage to the stack or personal injury. The flare, including the pilot, requires auxiliary fuel; a small propane tank is usually located near the flare to serve as pilot fuel. Sampling ports are located in the walls near the top of the stack where emissions monitoring is performed. A built-in staircase and platform are usually provided for access to the sampling areas. Stoichiometric combustion of methane has a flame temperature of 1871^{0}C (3400^{0}F). Insulation meltdown and internal stack explosion have occurred due to lack of excess air and high temperature interlock.

Siting of the flare is very important and should be considered in the design phase. Open flares can be located at ground level or can be elevated. Although some of these flares operate without external assist (to prevent smoking), most use steam or air, or the velocity of the gas itself, to mix the gas and air. Flares located at ground level can be shielded with a fence.

LFG is conveyed to the flare through the collection header and transfer lines by one or more blowers. A knock-out drum is normally used to remove gas condensate. The LFG is usually passed through a water seal before going to the flare. This prevents possible flame flashbacks which occur when the gas flow rate to the flare is too low and the flame front moves down into the stack.

Purge gas (N_2, CO_2, or natural gas) also helps to prevent flashback in the flare stack caused by low gas flow rate. A gas flow meter system is necessary to measure LFG flow to the flare. The gas flow should indicate both current flow and accumulated flow. For data storage, it is recommended that digital storage on magnetic or optical disks be used instead of paper recorder with an automatic pen to avoid maintenance problems. The total volumetric flow rate to the flame must be carefully controlled to prevent a flashback problem and to avoid flame instability. A gas barrier or a stack seal is sometimes used just below the flare head to impede the flow of air into the flare gas network.

Another important unit independent from the flare is the flame arrestor which is installed in the LFG inlet line. The main function of the flame arrestor is the absorption of heat, thereby preventing passage of flame. The flame arrestor is packed with aluminum plates which may become clogged with the combustion by-products. Pressure gauges and sampling ports must be installed on each side of the flame arrestor to indicate clogging and necessary removal for cleaning. Proper sealing of the flame arrestor in the housing is essential. Since a flame arrestor requires periodic factory cleaning, a stand-by flame arrestor should be kept on-site for use during maintenance activities. Also, in selecting a flame arrestor, an easily removable design should be considered for ease of cleaning and inspection.

Flares are typically designed with enclosed emission control to minimize NO_x, CO and hydrocarbon emissions while maximize the destruction of trace compounds such as vinyl chloride and aromatics. Particulate, SO_2 or HCl emissions that enter the flare will not be affected.

Thermocouples are used to monitor the flame in open and elevated flares. For the enclosed flares, ultraviolet (UV)-type flame detectors should be used. The UV flame detectors can detect instantaneous flame failure so the inlet valve can be shut before the vessel fills up with unburned gas.

The design and selection of landfill flares depend upon the required design and operating objectives (specific emission requirements for 98% NMOC destruction efficiency). In any case, flares should be designed and manufactured to provide the minimum operating temperature under a range of LFG compositions and flow rates.

4.4.4.2 Thermal Incineration

Thermal oxidation involves heating the gas stream to a high enough temperature for combustion, typically, between 1,500 and 2,000^{0}F. Parameters affecting incinerator performance are the LFG heating value, the water content in the stream and the amount of excess combustion air. The LFG heating value is a measure of the heat available from the combustion of the VOCs in the off-gas. Combustion of LFG with a heating value less than 1.86 MJ/m^3 (500 Btu/scf) usually requires burning auxiliary fuel to maintain the desired combustion temperature. Auxiliary fuel requirements can be lessened or eliminated by the use of recuperative heat exchangers to preheat combustion air. Off-gas with a heating value above 1.86 MJ/m^3 (500 Btu/scf) may support combustion but may need auxiliary fuel for flame stability.

Combustion devices are always operated with some quantity of excess air to ensure a sufficient supply of 0_2 The amount of excess air (the amount of air above the stoichiometric air needed for reaction) used varies with the fuel and burner type but should be kept as low as possible. Using too much excess air wastes fuel because the additional air must be heated to the combustion chamber temperature. Large amounts of excess air also increase flue gas volume and may increase the size and cost of the system. The air requirement is calculated as shown below.

Each molecule of CH_4 requires two molecules of O_2 for complete combustion according to the reaction:

$$CH_4 + 20_2 \text{ -----> } C0_2 + 2H_20 + \text{heat} \qquad (2\text{-}16)$$

Since air is 21 percent O_2 and 79 percent nitrogen, 9.5 molecules of air are required to supply the two molecules of 0_2. Each standard m^3 (35.7 scft) of CH_4 therefore, requires 9.5 m^3 (339 scft) of air for combustion. To ensure the reaction occurs efficiently, additional air is needed which is called excess air. Typically, a minimum of 10 to 20 percent excess air is needed to maintain a high destruction efficiency. In addition, excess air is also required to keep the reaction temperature from getting too hot. This extra air is called "quench air." As a result, the total excess air requirements may be from 100 to 250 percent above the theoretical combustion air required, depending on the operating temperatures and the CH_4 content of the LFG.

Example. Based on LFG flow of 100 cfm with 50% CH_4, 30% Co_2, 10% N_2, 10% H_20 the excess air requirements at different operating conditions are:

			Exhaust Gas Composition			
Operating Temperature C° (°F)	Exhaust Gas Flow m^3 (ft^3)	Theoretical Air %	CO_2	N_2	O_2	H_2O
			% Volume Basis			
760 (1400)	47.3 (1690)	230	4.8	74.3	13.6	7.4
982 (1800)	35.0 (1250)	140	6.4	7.29	11.1	9.6

Source: Adapted from Reference 10

Incinerators must be designed to handle minor fluctuations in flows. Packaged, single-unit thermal incinerators are available to operate on gas streams with flow rates in the range of 5.7 m^3/min (200 scfm) to about 1,430 m^3/min (50,000 scfm). However, excessive fluctuations in flow might not allow the use of incinerators and would require the use of a flare.

4.4.5 Energy Recovery Systems

The following four approaches have been adopted for recovering energy from LFG:

- upgrading the gas quality to pipeline quality for delivery to utility distribution systems;
- use of LFG directly as a boiler fuel;
- generation of electricity by the operation of an internal combustion engine with LFG; and
- use of LFG to fuel a gas turbine.

Typical LFG contains approximately 4,450 Kcal/m^3 (500 Btu/scf) of energy whereas pipeline-quality gas contains 8,900 Kcal/m^3(l,000 Btu/scf). The energy content of LFG varies widely depending upon the performance of the gas collection system and the stage of decomposition within the landfill. Generally, the collection of gas for energy recovery purposes has been limited to large landfills with over 1 million tons of solid waste in place. Recent experience has shown that gas may possibly be economically recoverable from smaller landfills, especially where energy prices are relatively high.

4.4.5.1 Gas Turbines

As described in Section 3.2.2.1, two basic types of gas turbines have been used in landfill applications: simple cycle and regenerative cycle. The gas temperatures from the power turbine range from 430 to 600^{0}C (800 to 1,100^{0}F). The regenerative cycle gas turbine is essentially a simple cycle gas turbine with an added heat exchanger. Thermal energy is recovered from the hot exhaust gases and used to preheat the compressed air. Since less fuel is required to heat the compressed air to the turbine inlet temperature, the regenerative cycle improves the overall efficiency of the gas turbine.

The size of the gas turbine system is based on the potential electrical output generated by using LFG as fuel. The gas turbine system is considered to be 30 percent efficient in converting the LFG to electrical energy [3].

Commercially available steam turbines range in size from approximately 100 Kw to over 1,000,000 Kw.

Achievement of high combustion efficiency requires the controlled mixing of fuel and air and the simultaneous satisfaction of several conditions:

- air velocities in the combustor below flame speed,
- air/fuel ratio within flammability limits,
- sufficient residence time to complete reactions,
- turbulent mixing of fuel/air throughout the combustion zone, and
- ignition source to start the reaction.

A factor to be considered in turbine operation is that turndown performance is poor (i.e., the gas turbines work best at full-load, but poorly if gas supplies are less than needed to supply the full-load operation).

4.4.5.2 Internal Combustion Engines

I.C. engines are being used at landfills because of their short construction time, ease of installation, and operating capability over a wide range of speeds and loads.

Almost all larger engines used in this application are made by three manufactures: Caterpillar, Cooper-Superior, and Waukasa. These engine-generators are developed and used not only with LFG but for numerous other applications. The combustion engines are commonly turbocharged-designs that burn fuel with excess air.

Various design and operating modifications including part modifications for corrosion resistance generally allow the engines to operate successfully at landfills. Lubrication systems may also be required for combustion engines utilizing LFG fuels. Halogen compounds in the LFG decrease the pH and subsequently increase corrosion of the engine parts. Chemical additives to the oil can largely neutralize these compounds and reduce corrosion. Additionally, nonmethane VOCs can build up in the engine oil; degrading the oil and reducing its effectiveness.

Positive crankcase ventilation may serve to reduce the concentrations of these NNOC. Another potential solution is to increase the block and oil temperature to maximize evaporation and minimize condensation. Because of the severity of the oil service, frequent oil changes may be required. Oil analyses, including Total Base Number (TBN), nitration and metal content, may be utilized to determine when replacement is warranted. These analyses may also be used to predict potential problems.

Various exhaust gas catalysts are sometimes used with pipeline-gas fueled I.C. engines to reduce emission pollutants in the exhaust gas stream. Experience have proven that the acidic LFG components (halogens, H_2S) break down most of the catalysts making this technique a significant expense(15). The presence of compounds such as halogens or sulfur might require some additional equipment such as scrubbers. Scrubbers reduce acid gases and particulates in air stream by transferring these compounds to a circulating liquid stream.

4.4.5.3 Boilers

Another energy recovery option is steam-electric generation that burns LFG in a boiler to produce high-pressure steam, which then drives a steam turbine to generate electricity. The steam turbines themselves require no special modification for use in an LFG project. However, the boilers used to burn the LFG and generate the steam must have burners designed to withstand the corrosion from the **H_25** and halogen compounds found in the gas.

Other parameters which should be considered in the design of steam turbine plant are:

- relatively clean water supply is needed for make-up, and
- accommodation to the variations of LFG composition without major adjustment to the combustion control system.

4.4.5.4 Potential Future Technologies

Several potential technologies are under development to improve LFG application: these include future flare design using low Btu's LFG 15 percent CH_4 with air regulation and long detention time, fuel cells, vehicular fuel, and possibly synfuels production.

Fuel cells are essentially electrochemical batteries. Fuel cells have been well established as a technology for generating energy for more than 20 years using natural gas. They are currently being considered for LFG applications in large municipal landfills [1,6].

Vehicular fueling with compressed CH_4 is of high interest for environmental and other reasons. Using LFG would involve some purification, possibly to near pipeline quality. The vehicle would have to be equipped with conversion kits, which include safety devices, to manage the high pressure involved.

Synthetic liquid fuels production is another application for LFG. Available technologies that could convert LFG to liquid fuels include hydrocarbon production by Fischer-Tropsch, methanol synthesis by various routes, including chemical catalysis at high pressures, or by partial biological oxidation[1].

4.5 GAS CONDENSATE SYSTEM COLLECTION AND CONTROL

Condensate management should be one of the key design elements of a LFG system. Condensate from LFG operations is classified as non-hazardous waste unless it exhibits a RCRA hazardous characteristic or is derived from RCRA listed wastes.

If LFG condensate is considered as a hazardous waste, the condensate cannot be returned to the landfill from which it was derived unless first treated.

Condensate characteristics are site specific. Since the regulations that apply to condensate management vary, the management options available at each facility will be based on state laws, restrictions of the local wastewater treatment plants, and other local decisions.

Water scrubber or knockout vessels are often used in control/recovery systems to remove liquids, primarily to prevent corrosion or line freeze-ups. If the condensate is not removed, it will collect in the lower portions of the system and plug the pipes, blocking the passage of gas and rendering the extraction system ineffective. Condensate sumps and traps must be designed to continuously drain condensate from all transmission lines under both negative and positive operating pressures while maintaining a seal between the gas stream and the atmosphere. A check valve may also be used at the outlet of the trap to prevent air or water flow back into the pipe. Water traps should be designed to withstand a minimum of 12 inches of water column more than the anticipated design vacuum in the system. Generally, condensate traps should be placed at the lowest points in the collection header system.

Condensate sump pumps usually have intakes above the motor casing and do not tolerate being pumped dry for long periods, the condensate collection sumps are rarely pumped completely dry. As a result, some water is always present in the sump and potentially in the conveyance system.

Condensate may also be managed by avoiding its formation. After initial condensate knock-out, the gas may be heated to avoid condensation in the lines or treatment equipment.

The temperature and moisture content of the extracted LFG and the ambient air temperature will impact the volume of the condensate that is produced from the extracted LFG. If pump tests are performed to establish the radial influence caused by various vacuum pressures, samples of the LFG can be collected and analyzed for moisture content and temperature. If pump tests are not conducted, estimates can be made assuming the LFG is saturated with moisture. This assumption will yield a conservative estimate for condensate generation as most operating LFG collection systems do not produce volumes of condensate predicted by assuming a saturated gas. Temperature of the gas can be measured by inserting probes into the landfill. Temperature of the LFG can also be estimated based on literature values for landfills similar in composition, age and dimension. Temperatures for the minimum ambient conditions that could occur in the piping system located above the low permeability liner can be estimated by surveying the climatological records for the geographic area. Temperature estimates for buried pipes can be estimated by contacting the local Soil Conservation Service and obtaining soil temperatures with depth for the region. Neither of these ambient temperatures will necessarily be the temperature that will be observed in the header system due to the heat content of the LFG, however, these temperatures represent a conservative approximation.

The calculation of condensate generated by cooling of LFG saturated with condensate can be approximated by assuming that condensate is similar in density to water and LFG is similar to air. This assumption permits use of psychometric charts developed for properties of steam. Using tables from psychometric charts, an estimation of the concentration of water (condensate) in air (LFG) can be made by dividing the humidity of the moist air by the specific volume of the moist air for the ambient temperature in the piping system as described in the preceding paragraph. This water concentration represents the concentration that will remain in the gas stream after cooling. The same calculation is made for the temperature corresponding to the temperature of the LFG. The volume of the condensate is then estimated by multiplying the water concentration at each temperature by the flow rate to determine the volume of condensate present in the gas stream at each temperature. The volume of the condensate is then estimated by subtracting the volume of condensate that will remain in the gas stream (ambient temperature) from the volume of condensate that exists in the gas stream at the temperature of the gas as it is extracted from the landfill.

Since LFG is seldomly saturated and the ambient temperature in the header system is usually higher than the ambient temperature of the surrounding soils or air, the volume of condensate computed by this method is conservative. This method generally over-predicts condensate generation rates. If a greater degree of accuracy is needed, it is recommended that a thermodynamic balance of the system be conducted. Since this level of accuracy is typically not needed for landfills, the methodology for this calculation is not presented in this document.

Condensate flow from gas collection piping is relatively low. In the northwest, condensate flows average approximately 0.015 gpm/acre of landfill. Due to low flows, the condensate collection piping (from gas header) is quite small and the pipe is usually sized based on cleaning equipment.

Removal of condensate in a knock-out pot is caused primarily by a pressure drop. The amount of condensate that will form from a pressure drop can be estimated as follows:

$$Q_{cond} = \frac{0.0203\ Q_{TOT}}{760 - 1.87 \Delta P_{TOT}}$$

where,

Q_{cond} = flow rate of condensate, m^3/min
Q_{TOT} = total gas flow rate, m^3/min
)P_{TOT} = total pressure drop, N/m_2

An alternative method to collect condensate is using a vacuum valve station (VVS), condensate collection tank and vacuum pump[16]. The VVS is installed between the gas and condensate collection manifold. Condensate from the gas header first fills the VVS, which acts as a float trap, to a point where an internal float ball opens a needle valve. When the needle valve is opened, the condensate is sucked from the VVS into the condensate manifold which drains into a condensate collection tank. An inverted stainless steel air release valve (as manufactured by APCO) is used at the VVS as the float trap. A vacuum pump is used to create the vacuum in the condensate collection tank and the entire condensate collection manifold. Deep well ejector pumps are used to pump the condensate from the collection tank into the next disposal system.

There is no comprehensive database on the chemical and physical characteristics of LFG condensate. Data that have been published shows that the aqueous phase of LFG condensate generally passes the TCLP regulated limits. If a non-aqueous phase liquid is present in the condensate, this fraction has been found to fail ignitability testing. Landfills that have been operating principally as municipal landfills are rarely found to have a non-aqueous phase fraction.

In preparing the proper management plan for condensate, it should first be determined if the condensate contains two phases. If the condensate does have a non-aqueous phase, management plans should include a phase-separation process to separate the non-aqueous phase liquids from the aqueous phase fraction. Since most condensates do not have two phases, only aqueous phase disposal issues are discussed in this document.

Disposal of gas condensate is an issue common to most landfill sites in humid climates. Methods of disposal for LFG condensate include:

- disposal at a local publicly owned treatment works (POTW) through municipal sewer lines or tank trucks,

- on-site treatment,

- injection of condensate back into the landfill, and

- aspiration of the condensate into an LFG flare.

Disposal at a local POTW depends on the physical and chemical characteristics of the condensate and the POTW's permit requirements.

Condensate recirculation is being practiced at numerous sites and is accomplished primarily through drainage into the collection well field at moisture traps, although this practice runs counter to conventional land practice. The return of condensate to the landfill will not be allowed unless the landfill is equipped with a composite liner and a leachate collection system (40 CFR Part 258).

Aspiration of condensate into LFG flares has been accomplished on several sites and promises to be an efficient and effective method of condensate disposal, provided the condensate is non-hazardous. Flare destruction efficiency is dependent on:

- flare temperature,
- flare residence time, and
- turbulence.

These are discussed in the previous sections.

Quenching tests must be conducted to ensure that condensate aspiration will not cause an unsatisfactory drop in operating temperature of the flare. Analysis of gas condensate quality, pre-aspiration flare emissions quality and emission quality during aspiration are typically required. Condensate is transferred from a liquid state to vapor at 870^{0}C (1600^{0}F) upon aspiration into the flare chamber. This requires approximately 12,000 Btu's of energy per gallon of condensate.

With the aspiration of condensate into the flare unit, draft velocities are created during condensate evaporation that could significantly change the retention time on which the original flare design was based. Recent applications of condensate aspiration, however, have not caused a decrease in destruction efficiencies. Only enclosed flame flares provide adequate residence time for condensate aspiration.

The operating efficiency of a gas flare is based on the turbulence condition. The aspiration of condensate will cause a change in the turbulence conditions inside the flare chamber.

4.6 ELECTRICAL

Electrical system design includes requirement for materials, equipment, and installation. Any future power needs that may be anticipated should also be included. In addition, reference codes, standards, specifications and area classifications should be used.

4.6.1 Codes. Standards, and Specifications

Codes, standards, and specifications include:

American Petroleum Institute (API)

- RP500 A -Recommended Practice for Classification of Areas for Electrical Installations in Petroleum Refineries.
- RP500 B -Recommended Practice for Classification of Areas for Electrical Installations at Drilling Rigs and Production Facilities on Land and on Fixed and Marine Platforms.
- RP500 C -Electrical Installations at Petroleum and Gas Pipeline Transportation Facilities.

American National Standard Institute (ANSI)

- C2 National Electrical Safety Code.
- C80.l National Electrical Safety Code Specification for Rigid Steel Conduit, Zinc Coated;
- C80.5 Specifications for Rigid Aluminum Conduit.

National Fire Protection Association (NFPA)

- 30 Flammable and Combustible Liquid Code
- 70 National Electrical Code (NEC)
- 496 Purged and Pressurized Encloses for Electrical Equipment in Hazardous Locations
- 497 Class I hazardous Locations for Electrical Installations in Chemical Plants.

Institute of Electrical and Electronics Engineers (IEEE)

- 141 Recommended Practice for Electrical Power Distribution for Industrial Plants;
- 518 The Installation of Electrical Equipment to minimize Electrical Noise Input to Controllers from external sources.

4.6.2 Areas Classifications

Classifications. A general rule is that the electrical components are not to operate in an explosive atmosphere. Whenever feasible, electrical equipment should be located in non—hazardous areas.

The areas to be classified fall into one of the following types as established for electrical installations in the NEC (NFPA 497):

Class I. Division I. Group D.

Class I, Division I, Group D are applied to locations where flammable gases or vapors, such as CH_4, are likely present in normal operating conditions.

Class I. Division 2. Group D.

Class I, Division 2, group D are applied to locations where flammable gases or vapors, such as CH_4, are normally confined and the flammable gases are present only in case of abnormal operation of equipment or in case of accidental rupture of pipe/container.

Unclassified Locations.

Unclassified areas fall into the following categories:

a. Locations that are adequately ventilated where flammable substances are suitably contained in well maintained closed piping systems which include only pipe, valves fitting are considered nonhazardous; Locations that are not ventilated, and piping systems inside do not have valves, fittings or other appurtenances are considered as nonhazardous.

b. Locations containing permanent sources of ignition, such as fired boilers, pilot lights, equipment with extremely high surface temperatures (above ignition point of the gases in the area) are not deemed hazardous.

4.6.3 Conduit Seals

Conduit seals are required on underground conduits between the ground surface and panels or equipment where sparking components are located.

4.6.4 Electrical Enclosures

Enclosures include power panels, control panels and other similar enclosures. According to NFPA 70-501-15, there shall be no exposed live parts (conduct electricity). In Class I locations, all live parts must be housed inside enclosures. Enclosure information is provided by the National Electrical Manufacturers Association (NEMA).

Non-explosion proof blower control panels may be mounted on an outside wall, or in a separate control room where positive pressure ventilation is maintained. Explosion proof equipment should be used on inside walls of the blower buildings.

4.6.5 Motors and Generators

Standards for motors and generators are provided by NEMA in ANSI/NEMA Standard MG-l. In LFG applications, all motors are to be enclosed. These include:

- Totally-enclosed nonventilated (TENV);
- Totally-enclosed fan-cooled (TEFC); and
- Explosion proof.

4.6.6 Installations

Electrical installations should be in accordance with API RP 540 and the NEC or local codes where applicable.

4.6.7 Grounding

All electrical systems require a reliable effective grounding system. Wiring and equipment in Class I, Division 2 locations must be grounded as specified in the NEC, latest edition.

4.7 SYSTEM MONITORING

A monitoring program should be established at all solid waste landfills. The monitoring program may be different depending on the end use of the LFG. Typically, in a landfill with blower/flare stations, the following areas need to be monitored:

- gas wells,
- collection system,
- condensate,
- flare, and
- LFG migration monitoring.

The following sections discuss monitoring parameters of each area, including locations, frequency, and monitoring activities associated with each.

4.7.1 Gas Wells

Following are monitoring parameters associated with gas wells:

4.7.1.1 Monitoring Locations

Monitoring locations at the wells should be established at the wellheads to monitor the LFG quality and quantity.

4.7.1.2 Frequency

The frequency of monitoring and adjustment is a site-specific determination based on how stable the system is. If the landfill cover is leaking and the system shows signs of air intrusion, the system requires weekly monitoring and adjustment. More stable systems may require monitoring and adjustment on a monthly or even less frequent basis.

4.7.1.3 Valve Position

A continuous record of the position of the valve regulating the vacuum applied to a wellhead should be kept as observed during routine inspection and maintenance. The valve position should be modified if monitoring parameters indicate that ambient air is intruding into the zone of influence for the well.

4.7.1.4 Gas Quality - Chemical

Methane. CH_4 content should be measured as an indicator of the quality of the LFG being extracted by the well. For a municipal solid waste landfill, measurements below 50 percent by volume may be an indicator that ambient air is intruding into the zone of influence of the well. This condition together with other parameters will help determine if the vacuum applied to the wellhead should be modified by altering the valve position. It is most common to measure CH_4 in units of “percent by volume” of gas. In MSW landfills, measurement of less than 45 percent CH_4 by volume should be used as the lower limit for modifying the valve position to reduce the opening.

CH_4 can be monitored through the sampling port on the wellhead using a hand-held instrument. New instruments which use infrared absorption to detect CH_4 concentrations are becoming available. The accuracy of these instruments are limited to ± 5 percent.

Oxygen. O_2 is measured as an indicator of ambient air intrusion. O_2 in the LFG should be in the range of 0 to 2 percent by volume. O_2 levels in excess of 2 percent may be indicative of ambient air intrusion into the system. It is important to monitor O_2 both as an indicator of ambient air intrusion and also as an indicator of the decomposition conditions in the landfill.

Portable O_2-sensing meters are typically used to monitor the O_2 content of the gas as sampled through the sampling port in the wellhead. Precaution should be taken in the calibration of these instruments as the sensitivity of the instrument is generally ±2 percent and a poorly calibrated instrument may lead to incorrect conclusions regarding well performance.

Carbon Dioxide. CO_2 is monitored to assess the condition of the landfill. Concentrations of CO_2 in excess of the concentration of CH_4 may be indicating that the landfill is not operating anaerobically. This condition is known as composting; composting can lead to landfill fires. The potential for composting conditions should be monitored by calculation of the composting ratio as shown in Section 4.7.1.6.

Many of the infrared devices developed to measure CH_4 can also be used to measure CO_2. Samples can be obtained directly through the sampling port in the wellhead.

4.7.1.5 Gas Quality - Physical

Pressure. Pressure should be measured at the wellhead sampling port in inches of water column (in. wc). One pound per square inch (psi) pressure is equal to 27.7 in. wc pressure. Gauge pressures should be recorded as negative indicating the pressure is less than atmospheric. Wellhead pressures significantly different than system pressures may be an indication of localized flow blockages.

Pressure is typically monitored using a magnehelic-type analog pressure gauge or hand-held pressure transducer gauge. Care must be taken to insure the monitoring instrument can measure anticipated pressures. Typical pressures at the wellhead range from -0 in. wc to -10 in. wc.

Temperature. If excessive ambient air is being pulled into the well, the temperature of the gas stream may decrease. The magnitude of the decrease will be dependent on the difference between the ambient temperature and the temperature of the gas within the landfill. Due to the difficulty in assessing these differences, temperature should be used in combination with other parameters as an indicator of ambient air intrusion.

Temperature is typically measured using a thermocouple attached to a digital-readout instrument.

Flow Rate. The flow rate is the measurement of the volume of gas flowing through the well per unit time. The flow rate is typically monitored to evaluate the flow at an individual wellhead in conjunction with CH_4 content and pressure to assess if control valve modifications are necessary. Since flow rate is dependent on temperature and pressure, it is important that both of these parameters are measured at approximately the same time as the flow rate measurement. Notation of these parameters will permit conversion of field data to standard conditions if needed for system evaluation.

Flow rate is typically calculated from measurements of the velocity of the gas and knowledge of the cross-sectional area of the pipe. Pitot tubes are the most common measuring device, however, some inaccuracy is imparted due to the moisture content of the gas. Thermal-mass flow indicators are also used to monitor flow rate. Both instruments can be used with the sampling ports installed at the wellhead.

Use of thermal-mass flow instruments requires that the density and heat carrying capacity of the gas stream is known. Since different locations of a landfill may generate different gas compositions, hence different density and heat carrying capacity, gas composition of different locations should be analyzed, and a chart of density and heat carrying capacity should be made. This chart should be used to adjust the difference in density and heat carrying capacity according to the manufacturer*s recommendations when thermal-mass flow instrument is used.

4.7.1.6 Analysis of Data

Following collection of data, calculations of several indices should be made in the field to assess overall system operation and landfill conditions.

Methane/Carbon Dioxide. The ratio of CH_4 to CO_2 should always be one or slightly greater than one. This index can be used to quickly assess ambient air intrusion. For example, a CH_4 to CO_2 ratio of 0.80 indicates that about 20 percent of the gas produced may be originating from aerobic decomposition or leaks in the landfill cover instead of anaerobic decomposition.

Composting Ratio. This ratio considers both O_2 and CH_4 in estimating the probable amount of air flow that results from ambient air intrusion. The ratio is:

$$\textit{Composting Ratio} = \frac{\left(\frac{1-\%CH_4}{57}\right)*0.21 - \left(\frac{\%O_2}{100}\right)}{\left(\frac{1-\%CH_4}{57}\right)*0.21 - \left(\frac{\%O_2}{100}\right) + \left(\frac{\%CH_4}{57}\right)} \qquad (2\text{-}16)$$

The maximum allowable value of the composting ratio reported, prior to taking action to improve conditions supporting anaerobic biodegradation, is 8. Higher values indicated that anaerobic processes are being impacted by 0_2 intrusion. Immediate measures should be taken to determine where O_2 intrusion is occurring.

4.7.2 Collection System

The objective of operating the gas collection system in a landfill is to maximize gas collection. This is achieved by having a well balanced vacuum in all parts of the system so gas is collected as possible without drawing air in through the landfill cover. Monitoring data will reveal how far out of balance or how much air is pulled into the system. The monitoring data can be used to determine adjustments required to achieve the operating goal.

This section describes the location, frequency and methodology for monitoring activities associated with the collection system.

4.7.2.1 Monitoring Locations

Monitoring points should be established at several locations in the collection system, for example at each gas well and at the inlet to the blower, to permit evaluation of the gas quality for discrete sections of the LFG collection system. Monitoring points are established so as to help isolate any blockages in the system.

4.7.2.2 Frequency

The frequency and schedule for monitoring points in the collection system are similar to that of the gas wells. These points should also be monitored as system operations indicate potential blockages in the collection system.

4.7.2.3 Gas quality — Chemical and Physical

Monitoring chemical gas quality in the collection system is the same as described for the gas wells.

4.7.3 Condensate

This section describes each of the units in the condensate management system and the monitoring requirements associated with each unit.

4.7.3.1 Remote Sumps or Tanks

To collect the LFG condensate from pipe headers, remote sumps or tanks are typically positioned at various locations in the LFG collection system. Each sump or tank is equipped with pumps (submersible or above ground). These sumps are fitted with high liquid level alarms as well as pump on/pump off level controls. The pumps should be inspected as part of the monthly inspection program to ensure that there are no obvious signs of irregular wear.

The control panel for each sump typically includes:

- a high liquid audible or visual alarm,
- moisture sensors, and
- a temperature limiter.

The control panel operation should be inspected and verified. Manufacturer*s recommended maintenance plan for the pumps and control/alarm systems should be implemented into the monitoring plan, and any routine observation requirements should be included in a monitoring log.

The condensate force main should be monitored monthly. The flow meters located at the sump pump discharges should be monitored to insure that there is no loss of flow between two monitoring points which would be an indicator of a potential leak in the main. Observation of the condensate flowmeter should be recorded on the monitoring log established for the sump inspection.

Spare parts for pumps should include one mechanical seal set per sump pump. As the spare seals are utilized during routine O&M, spare seals should be replenished at the site.

4.7.3.2 Central Units

Knock-out Pot. The knock-out pot will remove any moisture entrained in the LFG stream prior to the blower. The knock-out pot has no mechanical parts and therefore requires minimal monitoring. Monitoring should include inspection of the discharge lines to insure the lines appear in good condition and permit free drainage to the condensate storage tank. Valves permitting free-flow of the condensate from the knock-out pot to the storage tank should be maintained in the open position to prevent build-up of condensate in the knock-out pot.

4.7.4 LFG Migration Monitoring

4.7.4.1 Locations

Gas migration should be monitored both laterally and vertically. These include the following:

- spacing for probes,
- probes depth, and
- sampling frequency

Lateral migration monitoring is achieved by installing permanent gas monitoring probes at the periphery of the landfill to check for potential subsurface landfill gas migration is not escaping the landfill boundary.

Vertical migration is monitored across the surface of the landfill by moving portable instruments across the landfill. Locations where instruments measure concentrations above background will be noted and investigated further to check for vertical migration/outgassing.

4.7.4.2 Gas Quality - Chemical

Methane. CH_4 should be monitored as described in Section 4.7.1.4.

Carbon Dioxide. $C0_2$ should also be monitored if CH_4 is observed in order to determine if the CH_4 being monitored is the result of LFG migration or natural processes. Methods of monitoring $C0_2$ are discussed in Section 4.6.1.3.

4.7.4.3 Gas Quality- Physical

Temperature. Temperatures within a landfill are normally higher than ambient temperatures. Temperature measurements are most useful when compared over time, to determine if a rising or falling trend of LFG production is occurring. High-temperatures also indicate aerobic reactions which are occurring due to air infiltration into the landfill.

Pressure. By measuring the pressure, the operator know how well the system is balanced ,i.e., if he is achieving the same pressure differential at all collection points. Monitoring the barometric pressure when monitoring LFG is helpful in reducing and interpreting data. Barometric pressure should be measured using a manometer or similar instrument.

4.7.5 Flare System and Appurtenances

This section describes monitoring requirements associated with each unit in a blower/fare system.

4.7.5.1 Blower

Monitoring Requirements. Inspection of this unit should include reading the flow rate and pressure of the system and comparing these measurements to a standard curve developed by the manufacturer to determine whether the blower is operating within a safe range for the equipment. The pressure drop across the blower should also be monitored using magnehelic gauges at the entrance- and exit-way to the blower at ports included in the piping system to ensure that parts of the blower assembly have not worn or are causing excessive head loss across the unit. The blower should also be inspected and monitored according to manufacturer's specifications for the unit.

Frequency. It is recommended that monthly inspections be made, unless recommended otherwise by the manufacturer, to insure that operating parameters are within expected ranges. After the first year and every second year thereafter (at a minimum), comprehensive inspections by a representative of the manufacturer should be made to ascertain that no parts are wearing at a rate that is not expected. Should the equipment warranties recommend more frequent inspection, this frequency should be upgraded to the recommended levels.

4.7.5.2 Flame Arrestor

Monitoring Requirements. Monitoring of the flame arrestor consists of measuring the head loss across the flame arrestor to insure that operating head losses are not significantly above or below the losses expected for the unit. In general, flame arrestors require little maintenance (cleaning) and are rarely replaced in operating systems.

Frequency. Inspection of the arrestor can be infrequent since the flame arrestor does not have any moving parts. Monthly monitoring inspection conducted with several other portions of the gas collection and flaring system will be adequate.

4.7.5.3 Flare Unit

Monitoring Requirements. The flare unit should be capable of operating at >98 percent destruction requirement efficiency (DRE). In addition to DRE monitoring, the flare inlet should be inspected for:

- gas-flow rates;
- gas supply pressure;
- minimum operating temperatures; and
- influent gas parameters including CH_4, $C0_2$, and O_2.

Manufacturer's recommendations for minimum and maximum values for these parameters should be determined for the specific flare unit. Manufacturers typically specify a minimum supply pressure for a given flow rate. Inspection should include referencing operating parameters of flow rate and pressure drop against the design curve established for the flare. Inspection should verify that a sufficient delivery pressure is being supplied for the observed flow rate. If there is insufficient pressure, the blower should be inspected as noted in Section 4.7.5.1.

Minimum operating temperatures are generally specified by manufacturers to be 1,400^{0}C. The temperature of the flare unit should be inspected to insure that this parameter is being maintained. The CH_4 content and flow rate of the influent gas should be inspected as described below. Excessive operating temperatures should not occur since the flare unit should be designed with automatically adjusting air intake louvers. However, if excessive temperatures (i.e. > l,800^{0}C) are observed, controls for these louvers should be inspected.

Gas parameters including CH_4, O_2 and CO_2 should be inspected to insure that the operating concentrations are within acceptable ranges for the flare.

<u>Frequency</u>. Additional operating parameters including gas flow rates; gas supply pressure; minimum operating temperature; and inflow LFG parameters should be monitored more regularly. Monthly monitoring is recommended unless suggested otherwise by the manufacturer.

4.7.6 <u>Automation of Controls</u>

Generally, there are the following three forms of process control: local control, centralized control, and remote control. In a local control system, all control elements (i.e., indicators, switches, relays, motor starters, etc.) are located adjacent to the associated equipment. In a centralized control system, the control elements are mounted in a single location. These Systems may include a hard-wired control panel, a programmable logic controller (PLC) or a computer. Remote control can be accomplished several ways including by means of modems or radio telemetry.

To select the appropriate control scheme, the advantages and disadvantages of each control scheme must be considered. A localized control system is less complex, less expensive, and easier to construct. Centralized control systems are also easier to operate. Centralized data acquisition and control may include the use of computers or PLCs. Automated process control is a complex topic that is beyond the scope of this document; however, several points are worth considering. Often plant operators will be more familiar with traditional hard-wired control logic than with control logic contained in software. However, process logic contained in software is easier to change (once the operator learns the software) than hard-wiring. Therefore, if extensive future modifications to the proposed system may be anticipated, hard-wiring the process logic should be avoided.

Modems and radio telemetry can be used to control these systems remotely. Radio telemetry is typically used over shorter distances when radio transmission is possible. Modems are used with computerized control systems. Systems can also be equipped with auto dialers to alert the operator of a malfunction by telephone or pager.

A good instrumentation and control system design will assure that the individual components of the off-gas collection and control system are coordinated and operate effectively. This section will present:

- control elements used in the design,
- different degrees of automation,
- a list of minimal acceptable components, and
- a description of special instrumentation that may be used in these systems.

4.7.6.1 Control Elements

Gas Pressure Gauges. Pressure gauges in the operating range of the gas management system are readily available commercially. Several types are available; the only design consideration beyond the pressure range is corrosion issues with known compounds in certain landfills.

Methane Gas Detectors. Gas detectors may be placed in the feed manifold system of either active or passive collection systems to monitor the explosive range (or Btu content) of the recovered gas. Systems which burn the gas have different operating target values than systems which vent or otherwise dispose of it. The detectors may measure specific CH_4 (and other gas) content, using a GC; Combustible Gas Indicators (CGI), which measure the percent of lower explosive limit (LEL) of the gas being processed; or FID, which measure the concentration of VOCs relative to a calibration gas (which may be CH_4). The type of detector selected depends on the objectives of collection, whether the fuel value is to be recovered, and safety considerations for the landfill.

Alarms. The gas control system will usually require several alarms to ensure safe and efficient operation. As described above, alarms must be provided to ensure the water collection system does not overflow into the blower train. Alarms are required to alert for too rich a feed in the explosive range, or perhaps too lean a feed stream for combustion systems. Some blowers and vacuum pumps require alarms for overpressure or excessive vacuum in parts of the piping. The system may also contain flow rate alarms to indicate too much or too little gas movement.

Some degree of alarm protection is provided in the electrical system which serves the blowers or pumps in the form of thermal overload systems, circuit breakers or fuses to indicate when these systems have tripped.

Control Panel Layout. A control panel layout must be designed. This drawing will show, to scale, all electrical components and the associated wiring. Depending on the project, this control item may be submitted as a shop drawing by the instrumentation and control contractor. For example, the control panel for the condensate sump should include a high-liquid level alarm bell and the light; moisture sensors; temperature limiter, etc..

Logic Diagram. A logic diagram must be included if the process control logic is not apparent from the Piping and Instrumentation Diagram (P&ID). This diagram shows the logical relationships between control components. For example, the diagram may show that if a particular switch is placed in the "on position" and there are no alarm conditions, then the blower will turn on and activate a green indicator light. Another example is when the alarm switch is placed in the on position, signaling that the LFG is too rich, then the blower will be turned-off to prevent explosion situations in the flare.

The set of documents must have a legend to explain the symbols that are used. Regardless of the existence of the legend, standard symbols must be used wherever applicable.

4.7.6.2 Degree of Automation

The degree of automation is generally dependent on the complexity of the off-gas treatment system (if any), the remoteness of the site, and monitoring and control requirements. Typically, a trade-off is required between the initial capital cost of the instrumentation and control equipment, and the labor cost savings in system operation.

Systems designed for unattended operation would incorporate the greatest degree of automation of system controls. Control schemes may include the use of remotely located PLC, remote data acquisition, and modems and radio telemetry. System mechanical and electrical components would be selected on the basis of having optimum reliability while requiring minimum maintenance and adjustment.

4.7.6.3 Minimum Acceptable Process Control Components

At a minimum, the following process control components are required:

- pressure and flow indicators for each well,

- blower motor thermal overload protection,
- vacuum relief valve or vacuum switch to effect blower shutdown,
- pressure indicators at blower inlet and outlet,
- high level switch/alarm for condensate collection system, and
- explosimeter for sites with recently measured LEL levels greater than 10 percent.

O_2 monitoring and feedback controls are required on low emission engines. Automatic control of the stoichiometric ratio is by far the preferred method for long-term operation of LFG fired I.C. engines.

4.7.6.4 Special Instruments
Several specific instruments are common to the LFG control system that should considered in the design. These include:

- portable CH_4 and combustible gas meters (such as those originally developed for the natural gas industry and for mine safety),
- instruments that use infrared absorption for CH_4 measurement, and
- process GC.

CH_4 and combustible gas meters operate on two different principles. Both indicate the presence of any combustible gas, and need to be calibrated using CH_4 gas. Calibration should be performed according to the manufacturer's instruction.

Instruments that use infrared absorption have been developed specially for monitoring LFG. They operate on the principle that CH_4 strongly adsorbs light at certain wavelengths in the infrared range (> 400nm).

Process GC are used for onsite monitoring and control. However, laboratory facilities and trained chemists are required for monitoring operation.

4.7.7 Other Design Considerations

Other design parameters include:

4.7.7.1 Site Working Areas

Special working areas should be designated on the site plan for other contingency situations. Access areas to the landfill should be provided for checking the pipe headers, well heads, condensate traps and sumps. Arrangements for working areas may include locating such areas closer to the entrance gate. working areas are site specifics.

4.7.7.2 Office Buildings

At larger landfills where climates are extreme, a building should be provided for office space and employee facilities. Sanitary facilities should be provided for landfill personnel. At smaller landfills, trailers may be sufficient.

4.7.7.3 Utilities

Large landfills will need electricity, water, air, communication, and sanitary services. Remote sites may have to extend existing service or use acceptable substitutes. Portable chemical toilets can be used to avoid the high cost of extending sewer lines; potable water may be trucked in; and an electric generator may be used instead of having power lines run into the site.

4.7.7.4 Emergence Power

All LFG's extraction systems should be equipped with emergency power sources such as generators. To keep the blowers operating continuously, the generators should automatically turn on if the power supply falls below a certain voltage to avoid extensive buildup of potentially harmful or explosive gases in the event of a power outage.

4.7.7.5 Air

In the case where compressors are used to pressurize the extracted gas for combustion, an air supply will be needed for instrumentation control.

4.7.7.6 Water

Water is required for cooling and sanitary use. A water supply may also be required for fire protection of buildings and or equipment.

4.7.7.7 Fencing

At some sites, it is desirable to construct perimeter fences to keep out any trespassers or animals. If vandalism and trespassing are to be discouraged, a l.8-m (6-foot) high chain link fence is desirable. A wood fence or a hedge may be used to screen the operation from view. Locking vault covers and security guards may be required, in some areas to deter vandalism.

4.7.7.8 Lighting

If the landfill has structures (employee facilities, administrative office, equipment repair, or storage sheds, etc.) or if there is an access road in continuous use, permanent security lighting may be desirable.

4.7.7.9 Labor Requirements

LFG recovery systems typically do not require extensive labor commitments. A regular O&M schedule should be implemented to ensure the proper and uninterrupted operation of the system.

Depending on the LFG control system installed and the size of the facilities, one full-time operator may be needed to operate and maintain the gas collection system during the day. An automatic control system is designed to operate and control the system at night. A flare station may be left unattended, the computer maintaining the control system will shut down the collection system and notify the facility's off-duty operator via a dialer in case of malfunction.

4.7.7.10 System Safety

Due to the explosive nature of CH_4 gas, processing station electrical equipment and fixtures shall be typically classified as Class 1, Division 2, Group D of the NEC. Guidelines for Safety are presented in Article 501 of the NEC. For "Intrinsically Safe Systems" Article 504 of the NEC is recommended. Some local codes may be more restrictive than the aforementioned and should be examined before design.

If flares or burners are employed, flame arrestors should be installed in the inlet lines. Flame arrestors provide a means of reducing potential explosion hazards by preventing flashback of combustion gases from the burner through the process station.